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THE EFFECTS OF COOLING AND WARMING ON THE VITAL CAPACITY, FOREARM AND HAND VOLUME, AND SKIN TEMPERATURE OF MAN

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The changes in peripheral blood flow which follow cooling and warming in animals and man have been frequently studied, and there is no doubt that cooling usually reduces the peripheral blood flow while warming increases it, although there are a few, almost paradoxical, exceptions (Lewis, 1930; Pickering, 1932). The question where the blood is to be found when it is not in the peripheral vessels has, however, been consistently ignored or left unanswered, even by those who recognized that alternative pathways must exist (Maddock & Coller, 1933; Machle & Hatch, 1947). This is all the more striking since those working on long-term changes of the circulating blood volume following acclimatization to changes of temperature have considered the problem of blood storage (Barcroft, 1934; Bazett, Sunderman, Doupe & Scott, 1940), and since it has been clearly shown that the changes of peripheral blood flow which follow on cooling and warming must be very great (Barcroft & Nagahashi, 1921; Barcroft & Edholm, 1943). Quite apart from compensatory adaptations of the heart rate (Davy, 1845; Haldane, 1905), the cardiac output (Barcroft & Marshall, 1923), and the circulation rate (Smith, Allen & Craig, 1940), it might be expected that some redistribution of blood would occur when animals and men are exposed to sudden changes of temperature. Rein (1931) noticed that cooling greatly increased the mesenteric blood flow of dogs, but he did not consider this to be a compensation for a reduced peripheral blood flow. Müller and his pupils (Müller, 1905; Müller & Siebeck, 1907; Müller & Veiel, 1910; Glamser, 1911) studied this problem systematically, but their work has apparently been ignored. In a series of thorough experiments, and by a variety of methods applied to men and animals, these workers showed that the reduction of the peripheral blood flow which followed cooling was accompanied by an increase of the intra-abdominal and the cerebral blood flow, and that the opposite happened as a result of warming. Müller (1905) was unable to demonstrate that the human lungs played any part in blood redistribution, but Sjöstrand (1935) found that the lungs of mice which had been killed after cooling weighed more than the lungs of those which had been killed after warming and he suggested that the lungs could 'retain blood for the purpose of regulating heat'.

The blood content of the lungs has been studied by many workers. Daly (1928) showed that the quantity of blood in the lungs was variable. Evidence was subsequently produced which suggested that the lungs could act as a reservoir for blood both in animals (Hochrein & Keller, 1932) and men (Hamilton & Morgan, 1932), and the latter findings were repeated in a statistically significant series by Dow (1939). Experience with patients suffering from cardiac insufficiency (Peabody & Wentworth, 1917; Binger, 1923) and investigations by Budelmann (1937, 1938); Asmussen, Christensen & Sjöstrand (1939); McMichael & McGibbon (1939) and Jonsell & Sjöstrand (1941) confirmed the view that the volume of the air in the lungs varied inversely with that of the blood. Finally, Glaser & McMichael (1941) showed, in a statistically significant series, that removal of 380 ml. of blood from the human circulation was followed by an average increase of 153 ml. in the vital capacity and 181 ml. in the total air capacity of the lungs, which suggested very strongly that comparable changes had happened in the volume of the pulmonary blood. This seemed reasonable since it had been estimated that the human lungs held about 1 l. of blood (Blumgart & Weiss, 1929) or a little more (Plesch, 1937), and since Daly, Foggie & Hebb (1940) had observed changes of about 20 % in the total blood volume of the lungs of dogs. Changes of the alveolar CO_2 concentration have also been claimed to run parallel with changes of the blood content of the lungs (Mackay, 1943), but Roughton (1945) estimated that the average amount of blood contained in patent human lung capillaries and taking part in respiratory exchanges was only about 65 ml. at rest and 95 ml. during heavy work. These calculations appeared to refute all the above observations and estimations, for the lungs could not store more blood than they held. On the other hand, there is some evidence that, at any rate in animals, only part of the blood in the lungs is taking part in the respiratory exchanges at any one time. Sjöstrand (1935) has shown that mice and guinea-pigs have wide vascular passages in their lungs, and Prinzmetal, Ornitz, Simkin & Bergman (1948) have demonstrated in larger laboratory animals that these passages are 20–40 times wider than the capillaries. If such vascular spaces did exist in man it would be possible to reconcile most of the above findings with each other. Thus, in the absence of clear evidence to the contrary and in view of all the circumstantial evidence quoted above, it seems justifiable to conclude that the lungs may exert a reservoir function (using the word to mean any vascular region which can accommodate more or less blood to suit the needs of other parts of the body), and that changes in the volume of air in the lungs vary inversely with those of the blood. It seemed reasonable, therefore, to study the effects of cooling and warming on the peripheral blood flow and the vital capacity of human subjects.

METHODS

Subjects. Five healthy men aged 21–34 years took part in the experiment. All were trained to do research work, and they were helpful and unemotional. They wore shorts or slacks, and a shirt with short sleeves or rolled-up sleeves.

Vital capacity measurements. A flow-meter with a large dial was used, allowing measurements of the amount of air blown through it and of the rate of blowing. This apparatus offers practically no resistance to expiration and, if blowing is done at an even rate, it is more sensitive than a floating cylinder. All subjects had previously practised using the spirometer. They were not allowed to see the dial so that the possibility of unconsciously influencing the results was minimized. Three readings were always taken to the nearest 50 ml. at $1\frac{1}{2}$ min. intervals and averaged. Triplicate readings generally agreed to within 50 ml. and always to within 150 ml. The spirometer was kept at room temperature and carried into the cold-room or hot-room when measurements were made. The spirometer temperature was read from a mercury thermometer built into the apparatus and it remained within $\pm 1^\circ$ C. in any one test. With a vital capacity of 5·1 and at a barometric pressure of 760 mm. Hg a rise of temperature from 15 to 16° C. would decrease the volume of water vapour condensed in the apparatus by 6 ml. Small changes of the spirometer temperature would, therefore, not have given rise to false readings. Measurements of the vital capacity were made in preference to those of the total air capacity of the lungs because the greater experimental error of the latter (Glaser & McMichael, 1941) counteracts some of its advantages. Moreover, apparatus for the estimation of the total amount of air in the lungs cannot be easily carried from one place to another, and it is sensitive to fluctuations of the environmental temperature (McMichael, 1939).

Skin and rectal temperature measurements. The skin temperature was measured with a specially designed thermocouple and portable potentiometer allowing true readings to the nearest 0·1° C. (Glaser, 1949). The rectal temperatures were taken by clinical thermometers inserted for 5 min. with the precautions previously described (Glaser, 1949). Three marked points were chosen for skin-temperature measurements, one on the radial edge of the left forearm 1 in. below the cubital fold, one near the processus styloideus radii, and one on the tip of the left middle finger. Measurements of one point on the hand give adequate information of the type, though not necessarily the extent, of vasomotor reactions happening in the extremities when the body is cooled or warmed (Glaser, 1949), but three points were chosen so that the average skin temperature of the forearm and hand could be measured.

Forearm and hand-volume measurements. These were made by simple estimations of water-displacement. A 10 ml. graduated glass pipette was mounted alongside a brass cylinder in such a way that the bottom of the pipette and the side of the cylinder communicated through a brass U-tube. The cylinder was 21 in. high and had a diameter of 5 in. It was fitted with a plumb line and rested on an adjustable tripod, so that the pipette and cylinder could always be made vertical. The zero line of the pipette was just below the upper edge of the cylinder and the 10 ml. mark was about one-third of the way down. Measurements were made by immersing the left arm into the cylinder until a horizontal line drawn across the upper edge of the olecranon was exactly in line with the upper edge of the cylinder. The water temperature was made equal to the average temperature of the forearm and hand. The water level was adjusted by pouring water in from the top or removing it through a small tap at the bottom until it corresponded to the zero line on the pipette. The arm was then withdrawn and most of the water sticking to it was shaken back into the cylinder. The volume of the arm was calculated from the reading on the pipette. The apparatus was calibrated so that 1 ml. on the pipette corresponded to 200 ml. in the cylinder. It was easy to take readings to the nearest 0·05 ml. on the pipette, which corresponded to 10 ml. in the cylinder. With practice it was possible to make an estimation without leaving the arm in the cylinder for more than 15–30 sec., even though care had to be taken not to introduce errors either by pulling the upper arm skin and thus displacing the line drawn across the olecranon or by immersing the arm diagonally. Care was taken to avoid parallax errors.

This method seemed to be more satisfactory than a plethysmograph because the possible sources of error were easily controlled and such factors as the line across the olecranon or the amount of water sticking to the forearm after its withdrawal from the cylinder were constant throughout each test, whereas in an experiment involving changes of location and very great variations of environmental and skin temperature, a plethysmograph might have given rise to many technical errors (Barcroft & Edholm, 1943). The method used, moreover, had a scope and accuracy which was similar to that of the vital capacity measurements with which it was to be compared.

Air-conditioning. There was no single laboratory in which all tests could be performed. The temperature in the hot-room was 105° F. (wet bulb) and 95° F. (dry bulb), i.e. about 40·5 and 35·0° C. and there was an air movement of about 100 ft./min. The cold-room was at +1° C. with an intermittent air-movement of about 300 ft./min. Both rooms maintained their temperature with great constancy. They were in different buildings, but measurements taken before and after cooling or warming were taken in ordinary laboratories near each air-conditioned room (some twenty paces away). The laboratory temperature varied from 14 to 21° C. but never fluctuated by more than 2·5° C. in any one test. Owing to these day-to-day changes, however, the extent of cooling or warming to which the different subjects were submitted in similar tests was somewhat variable.

Procedure. The tests were spread over 7 months between July 1947 and February 1948. Each subject was tested three times, once at room temperature and in the hot-room, once at room temperature and in the cold-room and once at room temperature only. The subjects were tested one at a time and different tests on any one subject were performed in random order and at random intervals ranging from 2 days to 3 months, so that accidental effects of climate were cancelled out. All subjects were always tested at the same time of the day, so that accidental effects of daily rhythmical variations were excluded. About 1 hr. before each test they had a light meal containing small amounts of fluid and no caffeine. During the tests they sat still on a wooden chair with their left forearm and hand resting horizontally on a padded stool. The subjects' right hand was free to adjust the mouthpiece of the spirometer, insert the rectal thermometer, or hold a book; its movements, however, were reduced to the necessary minimum. After a period of adjustment at room temperature lasting 45–60 min. the first set of measurements was taken. Fifteen minutes after these had begun the subject went to the cold-room or hot-room and stayed there for 2 hr. He then returned to where the initial readings had been taken and remained there for another 1 hr. 30 min. Measurements were made at 30 min. intervals throughout. Thus the first reading in the air-conditioned room was taken at 15 min., and the last 1 hr. 45 min. after entering it; and the first measurements after returning to laboratory temperature were made 15 min. after leaving the air-conditioned room. Control experiments at room temperature lasted about 3 hr. A period of adjustment of 45–60 min. was again allowed, and readings were taken at 30 min. intervals. Each set of measurements lasted about 6–8 min. The order of measurements was always the same. Limb-volume measurements were always taken last and the arm immediately dried so that any effects which moisture or movement may have had on the skin temperature and arm volume would have worn off before the next set of readings. The forearm was moved from a horizontal to a vertical position whenever its volume was being measured, but significant postural changes of the limb volume only set in after several minutes (Waterfield, 1931).

RESULTS

The principal findings are summarized in Table 1. A typical record is given in Fig. 1. Times given are those at the beginning of each set of measurements.

At the end of cooling the vital capacity of all subjects had fallen by 200–480 ml., the forearm and hand volume by 50–160 ml. and the average skin temperature of three points on the forearm and hand by 8–23·1° C.; after

1 hr. 15 min. at laboratory temperature the vital capacity had risen again by 270–480 ml., the forearm and hand volume by 30–130 ml. and the skin temperature by 7·7–12° C. At the end of warming the vital capacity of all subjects had risen by 180–540 ml., the forearm and hand volume by 60–130 ml. and the average skin temperature of three points on the forearm and hand by 1·8–16·5° C.; after 1 hr. 15 min. at laboratory temperature the vital capacity of all subjects had fallen again by 100–300 ml., the forearm and hand volume by 70–150 ml. and the average skin temperature by 1·9–15·0° C. In control tests at room temperature the vital capacity fluctuated by up to 180 ml., the forearm and hand volume by up to 20 ml. and the average skin temperature of three points of the forearm and hand by up to 3·0° C.

TABLE 1. Changes of the vital capacity, forearm and hand volume, and skin temperature on cooling, and warming

	Cooling			Warming		
Subject	Vital capacity (l.)	Skin temp. (° C.)	Forearm and hand vol. (l.)	Vital capacity (l.)	Skin temp. (° C.)	Forearm and hand vol. (l.)
	Before entering cold-room			Before entering hot-room		
G.	5·20	30·0	1·55	5·28	33·6	1·52
J.	4·90	33·5	1·40	5·12	33·2	1·26
H.	5·38	32·8	1·61	5·60	28·8	1·59
N.	4·85	25·3	1·32	4·88	20·5	1·30
T.	4·80	32·3	1·36	5·10	26·0	1·11
	After 1 hr. 45 min. in cold-room			After 1 hr. 45 min. in hot-room		
G.	4·85	22·0	1·39	5·80	35·4	1·65
J.	4·42	10·4	1·35	5·30	38·7	1·38
H.	5·18	15·7	1·54	6·00	37·2	1·70
N.	4·68	10·5	1·26	5·42	37·0	1·36
T.	4·55	14·4	1·28	5·32	35·2	1·19
	After 1 hr. 15 min. at room temperature			After 1 hr. 15 min. at room temperature		
G.	5·20	30·0	1·52	5·60	33·3	1·56
J.	4·90	21·0	1·41	5·20	33·0	1·29
H.	5·55	23·4	1·60	5·70	23·5	1·55
N.	4·95	22·5	1·30	5·18	22·0	1·29
T.	4·83	22·4	1·31	5·22	23·7	1·08

Two subjects showed an initial rise of the rectal temperature in the cold-room, followed by a fall. In one of these the rectal temperature was still 0·05° C. above the initial level after 1 hr. 45 min., but in the other it had fallen by 0·4–0·8° C. After leaving the cold-room the rectal temperature of all subjects continued to fall and finally it was 0·75–0·95° C. below its initial level in four subjects and 0·3° C. below it in the fifth. During the last 30 min. at laboratory temperature the rectal temperature of four subjects fluctuated by 0·05° C. or less, while that of the fifth fell by 0·15° C. On entering the hot-room there was a slight initial fall of the rectal temperature in four subjects, but at the end of warming the rectal temperature of all subjects had risen by 0·45–0·95° C. On leaving the hot-room there was a slight rise of the rectal temperature in one subject, but after 1 hr. 15 min. it had fallen to the initial level or to within 0·1° C. from it in all subjects.

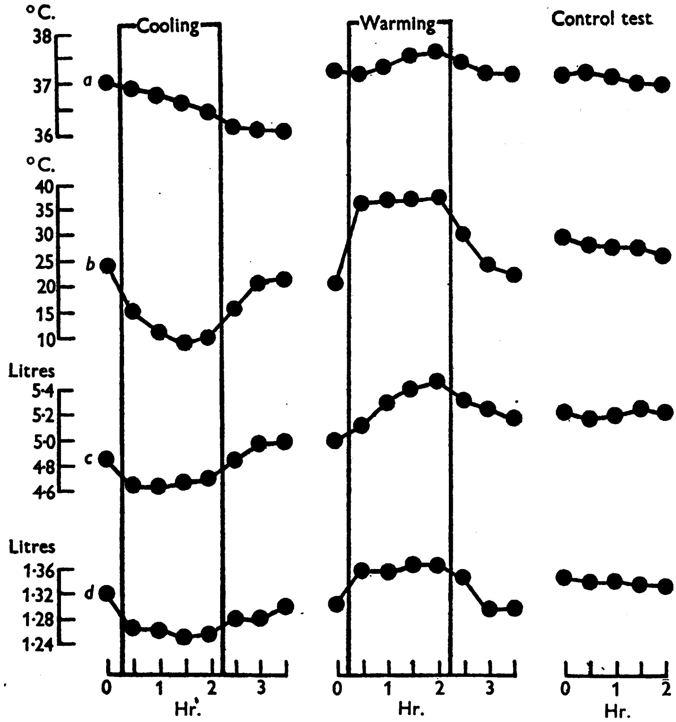

Fig. 1. The effects of cooling and warming. Typical result. Subject N. (average skin temperature of three points on forearm and hand). *a*, rectal temp.; *b*, skin temp.; *c*, vital capacity; *d*, forearm and hand volume.

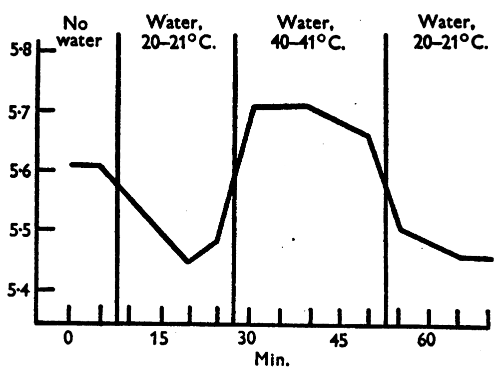

Fig. 2. The effects of cooling and warming of the lower limbs on the vital capacity. Subject G.

The effect of localized cooling or warming on the vital capacity. In order to find out whether cooling or warming of a part of the body would also result in changes of the vital capacity the following test was performed on one of the subjects. He sat still in an empty bath-tub at a room temperature of 22° C. (±1° C.) for 1 hr. Then water at 20–21° C. was quickly let in to the tub so that it covered the subject's lower limbs and buttocks up to the groin, but not his abdomen and chest. After 20 min. the water was quickly let out and the tub filled to the same level with water at 40–41° C. After 25 min. the water was quickly changed again to 20–21° C. The water was continuously stirred and its temperature kept constant. The vital capacity was measured at 5 min. intervals, taking duplicate readings each time. Cooling resulted in a moderate fall of the vital capacity and warming in a moderate rise (Fig. 2). Changes in the bath temperature were small, but the discomfort of greater changes might have interfered with even breathing. Another subject, aged 20, who had not taken part in the tests reported above, was submitted to a similar experiment. This time, however, warm water at 40° C. was first let in, and this was followed by a rise of the vital capacity amounting to 150 ml. Then the water was changed to 20° C. and this was not followed by any change of the vital capacity. Finally the water was changed to 40° C. and there was a further rise of 150 ml. in the vital capacity. When the water was removed the vital capacity fell to near its initial level. Two further subjects showed a rise of the vital capacity when their legs were immersed to the knees in water of about 40° C. and a fall of the vital capacity when their legs were immersed to the knees in water of 20° C.

DISCUSSION

In the above tests cooling was followed by a fall of the vital capacity, and the volume and temperature of the forearm and hand, while warming was followed by a rise of all these. On returning to normal laboratory temperature all these readings returned to their initial level or moved towards it by values which were greater than the experimental error. Changes of the vital capacity obtained at constant room temperature when only part of the body was cooled or warmed suggest that similar findings in the air-conditioned rooms were not caused by accidental environmental effects. The rectal temperature followed its own course which was not correlated with the other measurements, but which conformed closely with previous observations (Glaser, 1949). Fluctuations recorded in control tests at room temperature would appear to have been comparatively great, but it must be remembered that lightly clothed men tend to cool if they are sitting still at temperatures of 14–21° C. (Gagge, Winslow & Herrington, 1938) and that it may take several hours before thermal equilibrium is reached (Freeman & Linder, 1934).

It was suggested by Dastre & Morat (1884) that vasodilation in the peripheral circulation was always accompanied by vasoconstriction in the viscera. In view of the findings of Müller (1905), Müller & Siebeck (1907), Müller & Veiel (1910), Glamser (1911), Rein (1931), Sjöstrand (1935), and the results of the present investigation, a redistribution of blood between the inner organs and the periphery would seem to be one of the ways in which mammals adapt to changes of environmental temperature. It was suggested in a previous paper (Glaser, 1949) that various parts of the human body may change their temperature within comparatively wide limits, while the whole organism remains in a state of thermal balance or achieves balance at a new level. It now seems possible to expand this by suggesting that this balance is maintained by the appropriate movements of blood between the periphery (chiefly the superficial vessels of the limbs), and the organs contained inside the body cavities.

SUMMARY

1. In a cold medium the vital capacity of five subjects diminished, and so did the volume and skin temperature of their forearm and hand. In a hot humid medium all these increased. Return to normal laboratory temperature reversed these changes.

2. In four subjects immersion of the lower limbs in cold water was generally followed by a decrease of the vital capacity, and immersion in warm water by an increase.

3. It is concluded that cooling resulted in movements of blood from the extremities to the lungs, while warming caused movements in the opposite direction.

4. A simple apparatus is described, which will measure the water displacement of a limb under conditions when plethysmographic investigations are impracticable.

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